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"Massively Redundant Electromechanical Actuators"

August 30, 2014

Sponsored by
Defense Advanced Research Projects Agency (DOD)
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ARPA Order HR001135697-BASIC

Issued by U.S. Army Contracting Command – Redstone
Under
Contract No. W31P4Q-14-C-0041

Name of Contractor: ThermoDynamic Films, LLC
Principal Investigator: Dr. Richard Epstein
Business Address: 1313 Madrid Road, Santa Fe, NM 87505-4639
Phone Number: 505 310 1224

Effective Date of Contract: November 8, 2013
Short Title of Work: MREM Actuators

Contract Expiration Date: August 30, 2014
Reporting Period: April 24, 2014 – August 30,2014

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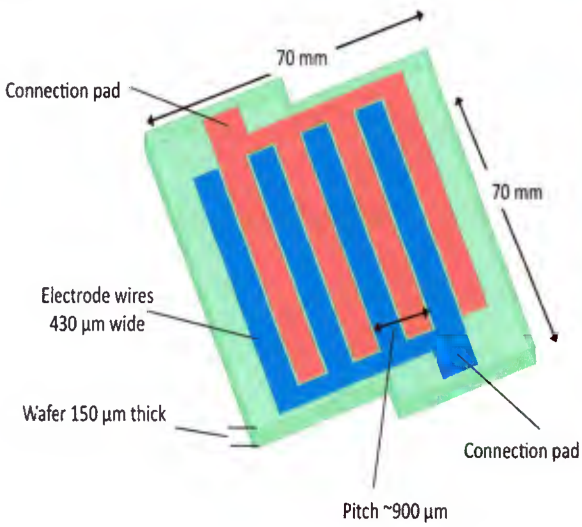
Final Report

August 30, 2014

During this reporting period, we continued developing the stator and slider electrodes and refined the methodology for evaluating and mitigating the failure risks of the MREM actuators.

TDF worked with Life BioSciences, Inc. (LBSI), to design and fabricate a test-bed MREM actuator with a single pair of stator and slider layers. The left side of Figure 1 shows schematics of the wiring layout for a half of a stator layer. The other half of the stator layer has a similar wiring layout. The right side of the figure shows a photo of the two halves of a recently fabricated unit. When the two halves are joined, the electrode wires are interleaved creating four sets of evenly spaced, independent stator electrodes.



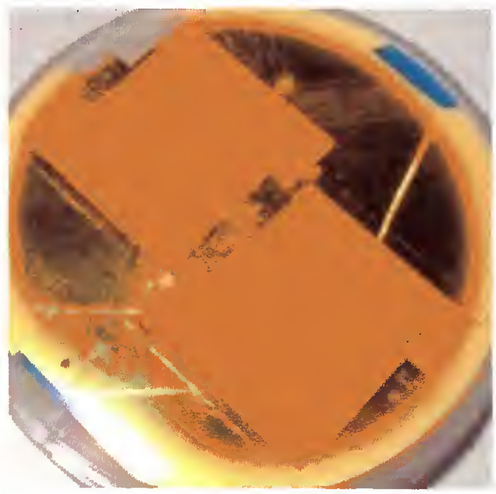


Figure 1. *Left: Wiring plan for one half of a stator layer. Right: Photo of the two halves of the latest stator.*

The left side of Fig. 2 shows the wiring layout for a slider layer. The slider has only one set of electrodes, which are maintained at ground voltage. The right side of Fig. 2 is and AFM image of the trench for one electrode. The trench is partially filled with copper and the surface is then flattened. The applying voltages to two of four of the stator electrodes provides the thrust that moves the slider layer.

Figure 3 is a photograph of the early experimental setup using a glass stator and an acetate slider.

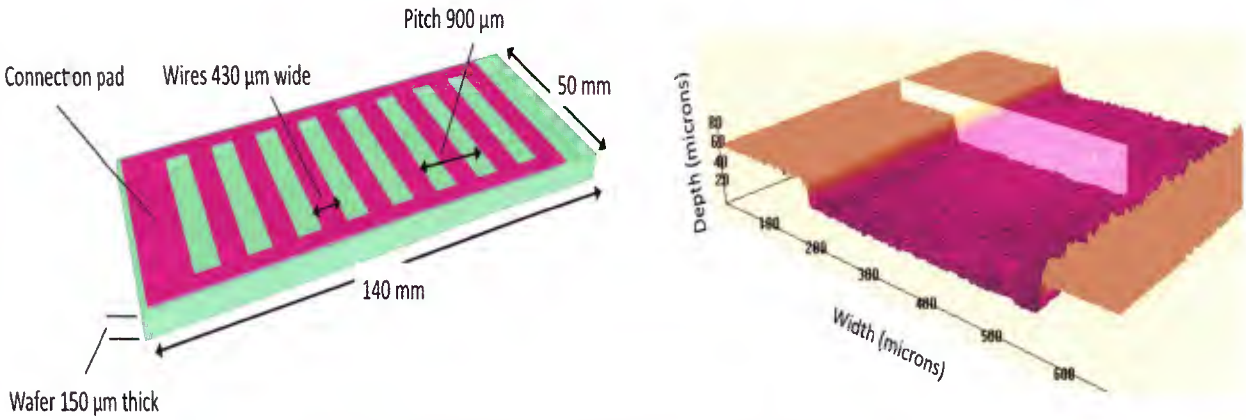


Figure 2. *Left: wiring plan for a slider layer and a photo of a section of the layer. Right: atomic force microscope image of a trench for a slider electrode.*

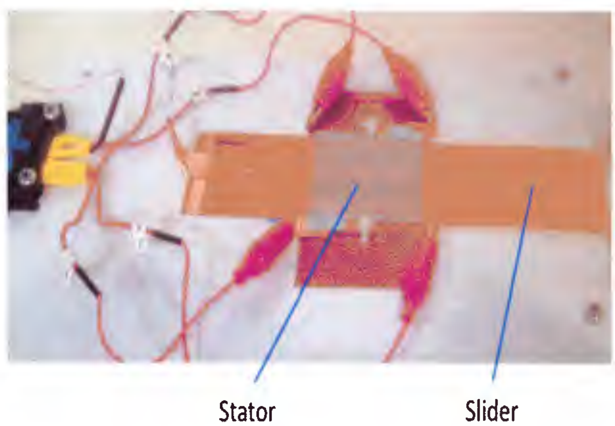


Figure 3. *Photo of set up of early acetate-based apparatus.*

The slider electrodes, which are grounded at zero volts, have a spacing or pitch between the electrodes of distance d. The four electrically independent and interleaved stator electrodes are subject to variable voltages V_1, V_2, V_3, and V_4 that are adjusted as the slider moves relative to the stator.

The failure risks of the MREM actuators are mitigated by the elimination of rolling components and any high-speed moving parts. The reliability is enhanced by the large redundancy inherent in the MREM architecture, the improved early fault-diagnosis through built-in self-test (BIST) and anti-jamming *mechanical circuit breakers.*

The reliability of the MREM actuators is limited by factors internal to the MREM actuators and external to them, as illustrated in Fig. 4. The internal factors include the reliability of the power electronics, the MREM circuitry, the computer processor and the durability of the moving sliders. The external factors are the reliability of

the power supply and the control signals that are supplied to the MREM actuator. These external factors can be made adequately reliable for aircraft usage by using triple or quadruple redundancy and voting architectures.

TDF focuses on ensuring that the factors internal to the MREM actuators have the required reliability. At the smallest scale, MEMS (micro-electromechanical systems) processes are used to manufacture reliable and reproducible stators and sliders for the actuators. These processes include well-established photolithographic, etching and deposition techniques. About 50 stator-slider pairs are combined into each independent drive module. A full MREM actuator will use about 20 independent drive modules. The performance of each drive module is monitored to assess whether it is functioning within specifications. Built-in self-test (BIST) sensors measure the force generated by each of the independent drive modules provide an early alert for any defects in any module. This warning system alerts the user that the MREM actuator performance is noticeably degraded long before it is about to fail. In addition to having large redundancy in the mechanical components and the circuitry, The MREM is designed to have redundant electronics. A separate power electronics unit supplies each drive module.

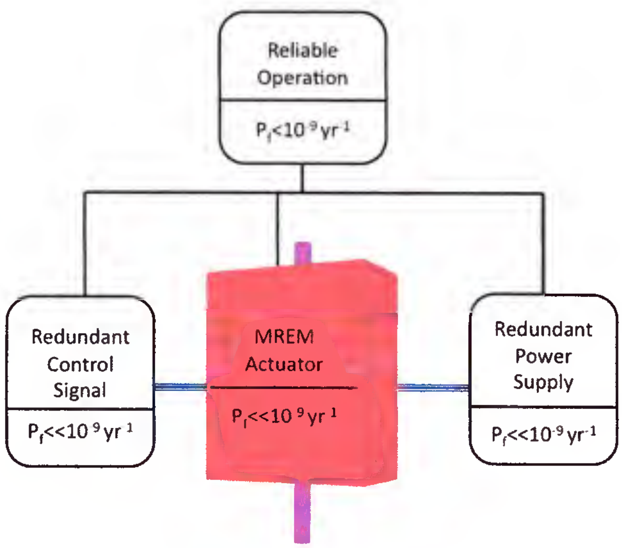


Figure 4*. Overall reliability of MREM actuators showing the relationship of internal and external factors*

Since the MREM actuator is a new architecture, TDF's approach is to rely on direct testing to determine the reliability of individual components. Stress testing each of the components in the laboratory over months will establish empirical upper limits of 10^{-3} yr^{-1} for the failure probabilities. These conservative failure rates can used to derive the overall reliability of the MREM actuators. Any components that were found to have failure rates near or above 10^{-3} yr^{-1} would be redesigned and rebuilt. The actuator is designed with sufficient power that it can operate at specs even if three of the individual modules are not functioning.